# Appendix XII

# A California Model of Climate Change Impacts on Timber Markets

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## Abstract

Several papers have now estimated the impact of climate change on global, regional, and national timber markets. This study explores the impact of climate change on California. The analysis examines two potentially important improvements on the information available in the literature. First, it relies on an ecological model to predict dynamic changes in ecosystems from transient climate scenarios. Second, it explores geographically detailed changes across the landscape for the climate change, the ecological change, and the economic impact. For each climate scenario, the ecological model predicts changes in productivity and biomes. These changes are then used to predict how forests in each California county will change. Forest changes, in turn, are used to predict the impact on harvesting and planting of softwood forests in each county from 2000 through 2100. At first, climate change increases harvests by stimulating growth in the standing forest. In the long run, these productivity increases are offset by reductions in the area where productive softwoods can grow. The present value of these ecological effects is beneficial but small (1%-3% gains). The long run consequences are harmful to the timber market, however, as the acreage of commercial forestland shrinks. The impacts are not felt uniformly across the state because the hot central valley tends to lose value, whereas the northern interior and north coast tend to enjoy large gains in most scenarios. California timber, however, may be highly vulnerable to global price reductions if warming increases productivity across most of the Earth. In this case, there would be large timber price reductions leading to economic losses to California timber producers of over $1 billion but very large gains to California consumers of as much as $14 billion.

## 1. Introduction

Climate change is predicted to have far-reaching effects on forests. Ecological models suggest that climate change will shift the geographic distribution of tree species (Emanuel et al., 1985; Shugart et al., 1986; Solomon, 1986; Neilson and Marks, 1994) and alter productivity (Melillo et al., 1993). Economic models predict that these changes are likely to increase the productivity of managed forests globally and lead to increased timber supply (Binkley, 1988; Bowes and Sedjo, 1993; Joyce et al., 1995; Burton et al., 1998; Sohngen and Mendelsohn, 1998; Sohngen et al., 1999, 2002; McCarl et al., 2000; Gitay et al., 2001). Although climate change may have a beneficial effect on the world's forests, it is unlikely to be beneficial in every location. Places that are too hot or too dry may find that forests shrink in their regions.

Recent studies of the climate change impacts on timber reveal that it is important to capture the dynamic path of ecological impacts (Sohngen and Mendelsohn, 1998; Sohngen et al., 1999, 2002). It is not enough to compare current production with a future equilibrium production level in 2100 because such comparisons do not reveal what happens throughout the century. Given that climate change is gradually unfolding over this period, that the ecological system is gradually responding, and that markets are slowly adapting, the dynamics of this problem are important. This study makes an important advance over past efforts to capture impact dynamics, in that this economic analysis is the first to rely on dynamic ecological modeling. In past studies, economists assumed linear dynamic paths on the basis of long-term equilibrium changes across ecosystems. However, in this study, an actual ecosystem model predicts the dynamic ecological changes for California.

This study also explores another critical issue in impact analysis. Previous studies have tended to rely on large-scale modeling. Typically, entire regions are captured in broad ecological models where the smallest unit of observation is actually a large and heterogeneous area. These ecological predictions are then aggregated to fit available economic data on large contiguous areas. In this study, we constructed a geographically detailed model designed to capture small-scale phenomena.

Climate change is expected to have far-reaching impacts on the distribution of ecosystems in California. The impact of these ecological changes on nonmarket values is explored in other studies associated with this effort. Because this study is limited to timber market impacts, a great deal of the southern portion of the state is not explored, as it is already too hot and too dry to support commercial forests. Although climate change is predicted to increase the amount of hardwood forests, this too is not included in this study because most of the California hardwood forest is not suitable for timber production.

## 1.1 Climate Scenarios

For our analysis, we relied on a set of climate change predictions that were identified for the California study. Two dynamic general circulation models (GCMs) were used to predict a relatively dry and wet scenario for the state. The Hadley model (HadCM2; Johns et al., 1997) predicts a very wet scenario and the PCM model run predicts a very dry scenario (Dai et al., 2001). Monthly data from the GCMs were used and downscaled to a 10 km resolution. The geographically detailed predictions of both GCM models were directly included in the ecological models for the state.

In addition to the GCM predictions, we also explored a set of climate change scenarios that assumes a uniform change in climate over all of California over all months. The uniform changes include a 3°C and 5°C change with no precipitation change, a 3°C change with an 18% increase in precipitation, and a 5°C change with a 30% increase in precipitation. The uniform scenarios capture a range of impacts for California predicted by a larger collection of GCM models and are less extreme with regard to precipitation changes than the HadCM2 and PCM GCM runs.

## 1.2 Ecological Model

The ecological modeling relies on MC1 (Daly et al., 2000; Bachelet et al., 2001) which is a dynamic vegetation model that simulates lifeform mixtures and vegetation types; ecosystem fluxes of carbon, nitrogen, and water; and fire disturbance (Lenihan et al., 1998). The model has been adapted to California. The ecological model offers two important improvements over past impact studies. First, the ecological model itself is predicting dynamic changes. In the past, economists have been forced to assume dynamic pathways from equilibrium ecological results. From linear climate change scenarios, economists assumed linear ecosystem change outcomes. Although this crude approach yielded a sense of ecosystem dynamics, relying on dynamic ecological predictions is highly preferable.

Second, the ecological model calculates geographically detailed predictions. In the past, ecological predictions have been aggregated over large areas to match available economic data. For example, some U.S. and global studies of timber used a single observation for the entire state of California (Sohngen and Mendelsohn, 1998; Sohngen et al., 1999, 2002). In this study, the geographically detailed ecological predictions are used to make geographically detailed economic analyses of every county in California.

The terrestrial biosphere model (MC1) uses detailed climate predictions to estimate dynamic changes in the distribution of biomes and the productivity of timber species across the state. Of course, this is a difficult undertaking as ecology has yet to determine precisely how ecosystems might change over time. There is disagreement about how long current stands might survive and how quickly new stands of new species might get established.

Biomes are ecological types that represent accumulations of different species. In this study, we focus on the forested biomes that support softwoods. We selected softwoods as the focus of this study because the bulk of California’s timber supply comes from softwoods. According to the California Statistical Abstract, 243 billion board feet out of a total of 258 billion board feet (94%) came from softwoods in 1996. Further, most of the forests in California are softwoods, 12.9 million acres, out of a total of 16.7 million acres of forests (77% in 1996).

Three biome types can support softwood timber species. The maritime temperate coniferous forest along the coast supports Douglas fir, western hemlock, Sitka spruce, western red cedar, (interior) lodgepole pine, Bishop pine, Monterey cypress, Monterey pine, and coastal redwoods. The continental temperate coniferous forest in the northern interior and lower Sierras supports Douglas fir, other true firs, ponderosa pine, Jeffrey pine, and (coastal) lodgepole pine. The boreal conifer forest along the high Sierras supports lodgepole pine, mountain hemlock, and other mountain pines.

MC1 predicts how much land is in each biome during each decade. This information is used to calculate the area of land that can be regenerated to timber. If the area is shrinking (growing), we assume that the regenerated land must also shrink (grow) proportionately. We do not assume, however, that the standing forest would change. There is reason to believe that the standing forest would not change as quickly as the model predicts for each decade. At the detailed geographical scale employed in this analysis, the ecological model predicts fairly large swings in territory between one biome and another during each decade. By altering planting only in response to these predictions, we may understate the full extent of the change. However, the model does not explicitly reflect the structure of a standing forest. In practice, long-lived species would not survive if thousands of hectares shifted in and out of each biome during each decade. By adjusting only regeneration, we can smooth these predicted rapid fluctuations of biomes in the model.

MC1 provides two alternative measures of productivity. The model calculates net primary productivity and change in forest carbon. The carbon measure reflects not only growth but also fire. We compute changes in growth rates on the basis of changes in net primary productivity (NPP) or carbon accumulation and compare the results. The changes of productivity $\theta_i(t)$ are assumed to be proportional to predicted changes in NPP and carbon accumulation. If NPP increases by 10%, for example, we assume that the merchantable part of trees in this system will grow 10% faster. This assumption implies that the merchantable part of trees remains in the same proportion to its limbs and roots and to the carbon on the forest floor. The effect of productivity changes on annual growth rates is:

$$V_i(t-t_0;m_i(t_0),\theta_i(t)=\int_{t_0}^{t}\dot{V}(s;m_i(t_0),\theta_i(s))ds\,. \tag{1}$$

The stock of forests is a function of the cumulative effect of $\theta_i(t)$ on the annual growth of trees. During early periods, when climate is just beginning to have effects, these changes will have only a small impact on timber approaching maturity. After many years, however, $\theta_i(t)$ will have a larger impact as the cumulative effect of growing faster increases the size of the stock.[1]

## 1.3 Economic Impact Model

A simple equilibrium model is used to estimate a baseline case for timber markets. Although historical harvests in California have been strongly influenced by harvesting old growth, current harvests are largely restricted to second-growth forests. We begin by making some assumptions

1. The studies in the literature actually make a range of assumptions about how climate affects productivity so that the specific form of Equation 1 depends on the underlying assumptions.

about the current inventory of forests in the state in each county. Ideally, we would prefer to begin with a detailed inventory that describes precisely how much acreage is in each age class. Unfortunately, such a detailed inventory is not available. The most we were able to secure is the aggregate acreage of timberland by county and the aggregate harvests in each county.

We assume that the private softwood forests in each county are currently fully regulated; that is, there are an equal number of hectares of softwood in every age category on private land. This assumption is likely to be accurate for the private lands across the state as a whole. However, it is unlikely that every county is fully regulated. Some counties probably have more land in younger age classes and some counties probably have more land in mature age classes. If this variation is random, it will not introduce a bias in the analysis.

We expect public lands throughout the state have a disproportionate acreage of older trees, many of them in advanced maturity. The available data from the state suggest that almost two-thirds of the softwood forests (8.1 million of 12.9 million acres) in California are in public hands, and most of these lands are federal. Harvests from public lands, however, account for only 13% of state volume even though the public controls two-thirds of the forestland. We expect that this low harvest production level partially reflects low productivity lands in the high Sierras and the southern parts of the state. More importantly, however, the low harvest rates reflect the multiple purposes of public lands. Public forests are expected to encourage conservation and produce many other nonmarket services. Timber production is not the highest priority service on public land.

Because public harvests are not near their biological potential, we assume that changes in the biological potential of public lands will not necessarily lead to changes in harvests. In other words, the harvests on public lands will be determined by social choices that are largely independent of climate change. These choices do not reflect biological constraints such as productivity or biome changes on public lands but instead reflect preferences for nonmarket services over timber. This analysis consequently concentrates on the private management of softwoods in California.

We begin the analysis by calculating timber harvests in the baseline case. The baseline case projects what California harvests and net revenues will look like into the future if there is no climate change. When looking at climate change, we use the baseline case as a reference, and assume that the aggregate acreage of softwood forestland in each county remains constant in the baseline. Although there will be a substantial amount of development throughout the state, most new development is expected to take place in hardwood forests, shrub land, and grasslands. Private softwood forests are not expected to be affected. In the baseline scenario, we also assume that forest productivity will remain constant; that is, we expect the trees to continue to grow at their current rates in each region of the state.

From available state data, we calculate the average productivity of forests in each county by dividing harvests by acreage. This analysis reveals two levels of average productivity across the state. The counties near the central valley, along the central coast, and in the northern interior tend to have slightly lower productivity. For this region, we estimate the following yield equation:

$$V(t) = \exp(12.31 - 145/t)\ , \tag{2}$$

where t is the rotation length. The forests along the northern coast and the Sierras around Sacramento tend to have higher average growth rates. We fit the following parameters for this more productive region:

$$V(t) = \exp(12.54 - 145/t)\ . \tag{3}$$

Both of these yield functions reflect the slow growing species in California. The average age that maximizes sustained yield, for example, is 145 years in both equations. Of course, the functions above mask the yield functions of individual species such as the difference between Douglas fir, redwoods, and ponderosa pine. Unfortunately, the ecological model cannot discern these specific species within their biomes.

Given the yield functions, we next calculate the rotation age. Relying on the well-known Faustmann equation, we choose a rotation length that maximizes the present value of net revenues:

$$\text{Max } W(t) = (P^*V(t) \exp(-rt) - C) / (1-\exp(-rt)) \tag{4}$$

We substitute \$400 per acre for the price of planting trees, C; 4% for the real interest rate, r; and \$0.41 per board foot for the price, P. Maximizing Equation 4 with respect to t reveals that the optimal rotation length for California forests is 62 years. We assume that all private softwood lands are managed at this rotation length, meaning that all softwood stands on private lands are cut when they reach 62 years of age. This estimate of rotation length is obviously an approximation, because stands on more fertile lands may be harvested at a younger age and stands on more marginal lands may be harvested later. The model is not able to distinguish land productivity beyond the regional data available.

The price per board foot varies across the state's counties from about \$0.35 to \$0.70 per board foot. The average for the state is \$0.41 per board foot. This price variation may simply be a measurement error. However, some of this variation may reflect permanent differences between counties due to access costs or other features of each county. We assume that the relative prices for timber across counties do not change over time or with climate change. We do explore a sensitivity analysis where we allow global prices to change with climate change.

To calculate the impact of climate change, we introduce the changes in growth rates and suitable softwood land that the ecological model predicts for each climate scenario. The changes are introduced as shown in Equation 1. This leads to new growth rates in each decade from 2000 to 2100. The ecological model also changes the predicted area of potential softwoods in each county. The model adjusts the acreage of softwoods that can be planted in proportion to predicted changes in aggregate acreage. The model then calculates the harvest and planting rates for each decade for each county and compares these rates to the baseline scenario. The model also calculates net revenue. Net revenue for each decade is equal to the harvest rates times the price per unit timber minus planting costs. The model calculates the change in net revenues in each decade from 2000 to 2100 and then calculates the change in net present value for the entire period.

Because the analysis is limited to the period between 2000 and 2100, the study abruptly ends in 2100. Impacts beyond 2100 are not calculated. Halting the analysis in 2100 ignores damages beyond 2100 that seem likely given the trends in the ecological data. Because limiting effects to the 21st century underplays some of the long-term harmful consequences of climate change on California's timber, future analysts may want to consider these longer term effects and extend their analyses beyond 2100.

Global models of timber impacts suggest that timber prices will be affected by climate change (Sohngen et al., 2002). A sensitivity analysis is explored that assumes that global prices change and therefore California prices change. Assuming that the price in each county changes proportionately with the change in global timber price, we then recalculate net revenues for each decade.

## 1.4 Results

We begin the analysis by calculating the baseline: a projection of California timber harvests, planting, and net revenues from 2000 through 2100 without climate change. Given the assumption that the private forests are currently fully regulated and that they rely on Faustmann rotations, the model predicts that current harvest rates for timber can continue indefinitely into the future. California will generate approximately $920 million of timber sales per year from 2.3 billion board feet. We assume that private softwood will generate 1.93 billion board feet annually with gross revenues of $793 million. In the baseline, 4.8 million acres remain in private softwood timber and 81,500 acres of this land are harvested every year when the trees reach age 62. The rest of the state's timber supply (370 million board feet) will come from softwood on public lands and from hardwoods. Finally, we assume that real prices will not change in the baseline and will remain at an average of $0.42 per board foot.

The baseline scenario predicts that gross timber revenues from private softwood will continue indefinitely each decade, yielding \$793 million annually. Subtracting planting costs, the private forests in California will yield a net annual revenue of \$760 million. Taking the present value of this stream of net revenue from 2000 through 2100 yields \$18.8 billion. This is the present value of the net revenue in the 21st century for the 4.8 million acres of private softwoods under the baseline assumptions.

Now, we explore what effects climate change will have on timber net revenue in California. We make the strong assumption that climate change will affect only private softwood harvests, basing the assumption on the fact that public softwood harvests and private hardwood harvests are currently only a small fraction of potential harvests. At this time, these harvests are not dependent on ecological constraints — they are determined by other factors. Although this does not necessarily mean that public softwood and all hardwood harvests will not be affected by climate change, it does suggest that it is hard to know how changes in climate would alter these harvests. For example, the public could react to reductions in private timber supply by increasing harvests allowed on public lands or they could reduce public harvests in parallel with private reductions.

It is possible that omitting public softwoods and all hardwoods from the analysis will introduce a small bias. In general, climate is likely to have the same impact on public softwoods as it does on private softwood forests. The softwood forests lost from warming will largely turn into hardwoods. Thus, if harvests in these two forest types parallel what is happening to the forests, public softwood harvests will rise slightly, then decline sharply, and hardwood harvests will largely rise. Given that these two sources are a small fraction of current timber supply in California and that they move in opposite directions, the omission of these two sources is not expected to seriously bias the analysis.

In this analysis, we explore how climate change would affect private softwoods. For each climate scenario, the ecological model predicts the amount of land in softwoods and the productivity for each county for each decade between 2000 and 2100. Table 1 presents the ecological results for three of these decades: 2020, 2060, and 2100. There are two measures of productivity, NPP and net additions of carbon. The two measures reflect many of the same changes in the ecosystem except that the carbon measure includes fire. As a result, the two measures generally agree with each other but they have slightly different reactions to moisture. The carbon measure is more sensitive to moisture. For example, the carbon measure responds more positively to the wet Hadley scenario with predicted reductions in fire and more negatively to the dry PCM scenario with possible increases in fire. The two measures do not have a strong response to higher temperatures, as they yield very similar outcomes for the 3°C and 5°C scenarios with no precipitation change. In general, however, it appears that the climate scenarios increase productivity with the only major exception being the long-term carbon measure in the dry PCM scenario.

**Table 1. Intertemporal impact of climate change on ecological parameters in California**

| Scenario | Productivity (NPP) | Productivity (carbon) | Acreage (softwoods) |
|---|---|---|---|
| **HadCM2** | | | |
| 2020 | 1.22 | 1.20 | 4,698 |
| 2060 | 1.21 | 1.27 | 4,357 |
| 2100 | 1.36 | 1.50 | 3,922 |
| **PCM** | | | |
| 2020 | 1.05 | 1.17 | 4,698 |
| 2060 | 1.20 | 1.04 | 4,259 |
| 2100 | 1.22 | 0.96 | 3,625 |
| **3.0°C, 0% P** | | | |
| 2020 | 1.00 | 0.99 | 4,695 |
| 2060 | 1.07 | 1.02 | 4,219 |
| 2100 | 1.03 | 1.06 | 3,788 |
| **3.0°C, 18% P** | | | |
| 2020 | 1.02 | 1.01 | 4,710 |
| 2060 | 1.14 | 1.08 | 4,275 |
| 2100 | 1.16 | 1.18 | 3,943 |
| **5.0°C, 0% P** | | | |
| 2020 | 1.01 | 0.99 | 4,719 |
| 2060 | 1.08 | 1.02 | 4,073 |
| 2100 | 1.01 | 1.03 | 3,337 |
| **5.0°C, 30% P** | | | |
| 2020 | 1.05 | 1.02 | 4,709 |
| 2060 | 1.20 | 1.12 | 4,006 |
| 2100 | 1.22 | 1.23 | 3,384 |

The effect of climate change on productivity is not the same across the entire state. Table 2 presents the results in 2100 for each major region of the state's forests. There is no effect in the southern portion of California because it is already too warm and dry to support softwoods even before climate change. According to the NPP measure, uniform dry scenarios will result in the central coast losing productivity and the central valley, north coast, and Sacramento receiving only small benefits. The northern interior is the only region to benefit in the dry scenarios.

**Table 2. Regional impact of climate change on ecological parameters in 2100**

| Scenario | Productivity (% Δ NPP) | Productivity (% Δ carbon) | Softwoods (Δ 000 acres) |
|---|---|---|---|
| **HadCM2** | | | |
| Central coast | 34 | 114 | 3 |
| Central valley | 45 | 48 | -292 |
| North coast | 12 | 17 | -396 |
| North interior | 42 | 54 | 5 |
| Sacramento | 30 | 39 | -291 |
| **PCM** | | | |
| Central coast | -1 | 87 | 0 |
| Central valley | 23 | -28 | -201 |
| North coast | 12 | 38 | -502 |
| North interior | 31 | -17 | -350 |
| Sacramento | 24 | -27 | -215 |
| **3.0°C, 0% P** | | | |
| Central coast | -13 | 12 | -1 |
| Central valley | -1 | -4 | -274 |
| North coast | 4 | 18 | -221 |
| North interior | 11 | 10 | -348 |
| Sacramento | 2 | 3 | -260 |
| **3.0°C, 18% P** | | | |
| Central coast | 7 | 32 | 0 |
| Central valley | 14 | 11 | -277 |
| North coast | 19 | 22 | -219 |
| North interior | 23 | 21 | -209 |
| Sacramento | 16 | 17 | -246 |
| **5.0°C, 0% P** | | | |
| Central coast | -26 | -7 | -5 |
| Central valley | 0 | -9 | -330 |
| North coast | 3 | 16 | -202 |
| North interior | 10 | 10 | -701 |
| Sacramento | 0 | 2 | -318 |
| **5.0°C, 30% P** | | | |
| Central coast | -1 | 18 | -1 |
| Central valley | 23 | 15 | -327 |
| North coast | 12 | 24 | -361 |
| North interior | 31 | 28 | -519 |
| Sacramento | 24 | 26 | -300 |

However, in the wetter uniform scenarios, only the central coast experiences a small effect and all other regions benefit. The PCM scenario resembles the uniform dry scenario in that the central coast is slightly damaged, but all other regions benefit. The Hadley scenario resembles the uniform wet scenarios except that even the central coast does well. The carbon measure treats the northern interior and Sacramento similarly to the NPP measure except for the PCM scenario, where it predicts large damages in both regions. The carbon measure results are much more optimistic about the central coast and the north coast than the NPP measure and slightly more pessimistic about the central valley. The carbon model's more optimistic predictions for the coastal regions and more pessimistic predictions for the central valley likely reflect fire predictions for the wetter coast and drier valley.

Table 1 also shows predictions of the acreage of softwood expected in each climate scenario. Climate change is expected to shrink the acreage of softwoods in California, turning a substantial fraction of softwood forests into hardwoods. The reduction increases with time in every scenario. Curiously, however, the reduction is only slightly sensitive to higher temperatures or less precipitation.

As with the changes in productivity, the changes in softwood habitat vary across the state, as seen in Table 2. There are only small changes in softwood acreage in the central coast, but that region has very few acres of softwoods to begin with (98,000). In many of the uniform climate change scenarios, the remaining regions seem to have the same absolute losses except for slightly larger effects in the northern interior. However, in percentage terms, these effects fall much more heavily on the private softwoods in the central valley and Sacramento regions with initial acreages of only 401,000 and 584,000 acres, respectively. In contrast, the percentage losses in the north coast and northern interior are lower because they contain so much more private softwood (1,960,000 and 1,850,000 acres, respectively). The Hadley scenario predicts much less harmful effects in the northern interior relative to the wet uniform change scenario because it predicts enormous increases in precipitation in the extreme northeastern corner of the state. These precipitation increases result in a substantial increase in softwoods in that location that offsets losses in the rest of the region. The PCM model predicts much more severe impacts on the northern coast and northern interior than the dry uniform scenario because it predicts substantial drying in the northern part of the state.

Given these changes in productivity and acreage, we next calculate what happens to the aggregate amount of land and average productivity in each climate scenario in each decade. Initial impacts are attributable strictly to changes in productivity. Harvests increase slightly because the standing trees are growing more rapidly. The reduction in softwood acreage reduces new land planted immediately but it takes many decades to see this effect on harvests. Table 3 shows the effects on net revenue in 2020, 2060, and 2100.

**Table 3. Annual timber net revenue (millions of dollars/year)**

| Scenario | 2020 | 2060 | 2100 |
|---|---|---|---|
| **NPP model** | | | |
| HadCM2 | 775 | 866 | 869 |
| PCM | 784 | 772 | 784 |
| 3.0°C, 0% P | 775 | 744 | 680 |
| 3.0°C, 18% P | 778 | 761 | 726 |
| 5.0°C, 0% P | 781 | 757 | 653 |
| 5.0°C, 30% P | 785 | 792 | 743 |
| **Carbon model** | | | |
| HadCM2 | 780 | 800 | 836 |
| PCM | 791 | 891 | 846 |
| 3.0°C, 0% P | 786 | 709 | 636 |
| 3.0°C, 18% P | 788 | 709 | 667 |
| 5.0°C, 0% P | 787 | 715 | 601 |
| 5.0°C, 30% P | 792 | 739 | 674 |
| **Baseline** | **760** | **760** | **760** |

Relative to the baseline of $760 million per year, the net revenues are higher in 2020 for every scenario. However, in all the uniform change scenarios, net revenues strictly decline with time. Effects diverge across climate scenarios by 2060. Using NPP as a measure of productivity, net revenues under the uniform wet scenarios are higher through 2060 and then fall off and become damages. The net revenue in the uniform dry scenarios has already fallen below the baseline by 2060, and continues to shrink with time. Interestingly, the PCM scenario is beneficial even though it is dry, and the Hadley scenario is the most beneficial of all the climate change scenarios. By 2100, the only two scenarios that are beneficial are the two GCMs. Using the carbon measure of productivity, the two GCM scenarios remain the most beneficial in the far future but in this case, the PCM scenario is actually more beneficial than the Hadley. The carbon measures also imply that all the uniform change scenarios lead to falling net revenue over time. With the carbon measure, however, these paths change only slightly with more severe temperature increases or with less precipitation.

In Table 4, we examine the present value of the streams of net revenue displayed in Table 3. Using a 4% real interest rate, we calculate the change in the present values of net revenue caused by climate change. These calculations take the difference in the stream of net revenue under each climate scenario relative to the baseline. The result, as shown in Table 4, reveals that the effect of climate change on California timber is positive. In every scenario, the present value of net revenues increases. The benefit from warming ranges from $58 million (0.3%) in the 3°C, 0%

**Table 4. Present value of impact of climate change on timber (millions of dollars) (baseline $18.8 billion)**

| | Climate scenario | | | | | |
|---|---|---|---|---|---|---|
| | **HadCM2** | **PCM** | **3.0°C, 0% P** | **3.0°C, 18% P** | **5.0°C, 0% P** | **5.0°C, 30% P** |
| **Carbon model** | | | | | | |
| **State** | **599.6 (3.2%)** | **1,188.7 (6.3%)** | **160.5 (0.8%)** | **213 (1.1%)** | **195.6 (1.0%)** | **361.6 (1.9%)** |
| Central coast | 75.8 (18.2%) | 152.9 (36.6%) | 37.3 (8.9%) | 43 (10.3%) | 35.3 (8.5%) | 42.1 (10.1%) |
| Central valley | 50.3 (4.1%) | -53.8 (-4.3%) | -20.2 (-1.6%) | -8.5 (-0.7%) | -21.6 (-1.7%) | -1.4 (-0.1%) |
| North coast | 4.9 (0.1%) | 1,140.7 (11.9%) | 125.6 (1.3%) | 96.3 (1.0%) | 148.7 (1.6%) | 188 (2.0%) |
| North interior | 419.2 (7.7%) | -49.6 (-0.9%) | 5.8 (0.1%) | 50.8 (0.9%) | 24.3 (0.4%) | 100.5 (1.8%) |
| Sacramento | 49.3 (2.4%) | -1.6 (-0.1%) | 12 (0.6%) | 31.4 (1.5%) | 8.8 (0.4%) | 32.5 (1.6%) |
| **NPP model** | | | | | | |
| **State** | **755.9 (4.0%)** | **347.7 (1.9%)** | **57.6 (0.3%)** | **180.9 (1.0%)** | **169.2 (0.9%)** | **373.5 (2.0%)** |
| Central coast | 19.6 (4.7%) | 13.9 (3.3%) | 6.6 (1.6%) | 11.7 (2.8%) | 4.8 (1.1%) | 13.8 (3.3%) |
| Central valley | 29.8 (2.4%) | 5.2 (0.4%) | -32.0 (-2.6%) | -19.4 (-1.6%) | -30.9 (-2.5%) | -5.3 (-0.4%) |
| North coast | 259.1 (2.7%) | 106.5 (1.1%) | 48.6 (0.5%) | 85.5 (0.9%) | 97.4 9-1.0%) | 153.6 (1.6%) |
| North interior | 402.5 (7.4%) | 161.5 (3.0%) | 37.1 (0.7%) | 87.2 (1.6%) | 88.9 (1.6%) | 177.1 (3.2%) |
| Sacramento | 44.9 (2.2%) | 60.6 (2.9%) | -2.7 (0.1%) | 15.9 (0.8%) | 9.1 (0.4%) | 34.3 (1.7%) |

scenario with carbon to $1.2 billion (6.3%) in benefits in the PCM scenario using NPP. The present value calculation implies that the benefits of the early increases in productivity outweigh the damages from the eventual loss of softwood habitat. The two GCM scenarios are the most beneficial with benefits ranging from $348 million to $1.2 billion. The uniform wet scenarios are better than the dry scenarios and the 5°C uniform scenarios are better than the 3°C scenarios. In general, with the dry scenarios, the NPP measure is more optimistic and with the wet scenarios, the carbon measure is more optimistic. Again, this difference in predictions likely results from the fact that the carbon measures include the effect of fire.

Although warming raises timber net revenue across the state, it does not do so in every region. The central valley is expected to be damaged by warming in every scenario except the Hadley. The PCM scenario with the carbon model also leads to damages in the northern interior and Sacramento regions, although these effects are small in percentage terms. The PCM scenario predicts curiously large benefits in the central (36%) and north (12%) coast in the carbon measure and the Hadley predicts large benefits in the northern interior (7%-8%). In general, however, the benefits from warming tend to have a smaller effect in each region, in the range between 1% and 3%. Across the uniform climate change scenarios, regions generally receive more benefits (or less damages) as it warms or gets wetter.

The results in Tables 3 and 4 are based on changes in California forest productivity. In this analysis, we have assumed that the prices of timber will remain constant. Of course, it is unlikely that timber supplies will change from 1% to 6% and not change prices. The problem is that we cannot assume that just because California supply changes, that global supplies will change proportionately. The California supply of timber is a poor measure to use to predict global timber prices.

In the analysis that follows, we rely on external sources to predict changes in global prices. We then change the California prices in each county proportionally with the changes in global prices. Sohngen et al. (2002) constructed a dynamic model of global timber to allow them to measure the effect of climate change on global timber prices. The model is more sophisticated than the economic model used only for California because it solves for dynamic equilibrium market outcomes. However, the global model cannot be fit perfectly to the California scenarios because the climate change scenarios are not the same in both studies. The results of the global versus the California models are slightly different, partly because of differences in climate assumptions and partly because of differences in scale. The global model, like the California model, predicts increases in forest productivity over time. However, the global model predicts larger initial benefits as short- rotation semitropical forests respond quickly to carbon fertilization effects. The global model also predicts that the benefits will continue to increase over the century as forests increase in size and productivity globally. These long-term benefits seen elsewhere in the world do not occur in California as it becomes relatively too hot and dry for softwoods.

In Tables 5 and 6, a single set of climate change global prices from Sohngen et al. (2002) is used to predict what will happen to California prices. These prices fall over time because of the predicted increases in global production. Adding these prices to the baseline scenario reveals that even if climate change had no effect on production in California, the resulting net revenues would still fall because of falling prices. Adding the changing prices to the changing production levels gives very different results in Table 5 compared to those presented in Table 3. When prices are held constant (Table 3), net revenues increase with the two GCM scenarios and

**Table 5. Annual timber net revenue with falling global prices (millions of dollars/year)**

| Scenario | 2020 | 2060 | 2100 |
|---|---|---|---|
| **Carbon model** | | | |
| HadCM2 | 699 | 617 | 620 |
| PCM | 709 | 688 | 628 |
| 3.0°C, 0% P | 704 | 547 | 470 |
| 3.0°C, 18% P | 706 | 546 | 494 |
| 5.0°C, 0% P | 705 | 551 | 445 |
| 5.0°C, 30% P | 709 | 570 | 499 |
| **NPP model** | | | |
| HadCM2 | 694 | 669 | 644 |
| PCM | 703 | 596 | 581 |
| 3.0°C, 0% P | 695 | 573 | 503 |
| 3.0°C, 18% P | 697 | 587 | 538 |
| 5.0°C, 0% P | 699 | 584 | 484 |
| 5.0°C, 30% P | 703 | 611 | 551 |
| **Baseline** | **760** | **760** | **760** |
| Baseline with falling prices | 681 | 586 | 562 |

increase and then fall with the uniform scenarios. With prices falling over time (Table 5), net revenues fall in every climate scenario over time. Relative to the baseline with no climate change, there are damages for producers in every decade that increase steadily with time.

In Table 6, we take the present value of the stream of annual damages reported in Table 5 associated with including global prices in the analysis. Including global price effects, climate change has a negative effect on California timber producers. Despite the beneficial effects on production in California, climate change causes price reductions that lead to damages in every scenario. The damages range from $0.1 billion to $1.4 billion. Every region has net damages except for the central coast in the carbon model. Because prices reduce net revenues equally in all regions, the proportional damages are similar across the remaining regions except for slightly larger damages in the central valley. Note that with falling prices, the absolute size of damages is much larger in the regions with more timber (north coast and northern interior).

This sensitivity analysis reveals that California timber is much more sensitive to global price reductions from increased global production than it is to production reductions in the state. If there are no changes in prices, climate effects are beneficial for timber producers and could even deliver benefits as high as $1 billion. However, if prices fall because of global increases in forest productivity, California timber producers will likely suffer damages that could easily exceed $1 billion.

**Table 6. Present value of climate change impact on timber with falling global prices (millions of dollars)**

| | Climate scenario | | | | | |
|---|---|---|---|---|---|---|
| | **HadCM2** | **PCM** | **3.0°C, 0% P** | **3.0°C, 18% P** | **5.0°C, 0% P** | **5.0°C, 30% P** |
| **Carbon model** | | | | | | |
| **State** | **-1,084.6 (5.8%)** | **-616.1 (3.3%)** | **-142.5 (7.6%)** | **-1,381.8 (7.4%)** | **-1,395.9 (7.4%)** | **-1,261.9 (6.7%)** |
| Central coast | 26.4 (6.3%) | 90.9 (21.8%) | -3.5 (0.8%) | 1.1 (0.3%) | -5.1 (1.2%) | -0.3 (0.1%) |
| Central valley | -62.2 (5.0%) | -149.1 (12.1%) | -118.8 (9.6%) | -109.3 (8.8%) | -119.5 (9.7%) | -103.3 (8.4%) |
| North coast | -785.2 (8.2%) | 134.5 (1.4%) | -680.5 (7.1%) | -703.1 (7.30%) | -661.3 (6.9%) | -628.8 (6.5%) |
| North interior | -127.1 (2.3%) | -514.1 (9.4%) | -459.1 (8.4%) | -423 (7.7%) | -444.3 (8.1%) | -383.8 (7.0%) |
| Sacramento | -136.4 (6.6%) | -178.4 (8.6%) | -162.8 (7.9%) | -147.3 (7.1%) | -165.8 (8.0%) | -146.4 (7.1%) |
| **NPP model** | | | | | | |
| **State** | **-984.8 (5.2%)** | **-1,311.1 (7.0%)** | **-1,547.1 (8.2%)** | **-1,448.2 (7.7%)** | **-1,454.0 (7.7%)** | **-1,291.0 (6.9%)** |
| Central coast | -20.4 (4.9%) | -24.1 (5.8%) | -29.9 (7.2%) | -25.9 (6.2%) | -31.4 (7.5%) | -24.1 (5.8%) |
| Central valley | -80.6 (6.5%) | -100.3 (8.1%) | -130.0 (10.5%) | -119.8 (9.7%) | -128.7 (10.4%) | -108 (8.7%) |
| North coast | -594.4 (6.2%) | -719.2 (7.5%) | -769.9 (8.0%) | -740.1 (7.7%) | -728.8 (7.0%) | -684 (7.1%) |
| North interior | -148.3 (2.7%) | -340.0 (6.2%) | -439.7 (8.0%) | -399.8 (7.3%) | -397.4 (7.3%) | -147.3 (7.1%) |
| Sacramento | -1,41.1 (6.8%) | -127.5 (6.2%) | -177.5 (8.6%) | -162.6 (7.9%) | -167.8 (8.1%) | -147.3 (7.1%) |

However, the very same price reductions that adversely affect timber suppliers provide large benefits to California consumers. The price elasticity of demand is steeper than the price elasticity of supply, so that price declines lead to more consumer surplus gained than producer surplus lost (Sohngen et al., 2002). Further, California consumes much more timber than it produces. The state exports 341 million board feet to other western states but imports 1,278 million board feet for a net import of 936 million board feet. Total California production is therefore 1,598 million board feet but total consumption is 2,535 million board feet.

The consumer surplus benefits from lower prices increase over time with population growth. As can be seen in Table 7, there are large benefits to consumers from the lower prices. In the slow growth scenario, the benefits are estimated to be $490 million in 2020 growing to $1 billion in 2060 and beyond. In the fast growth scenario, the 2020 estimates are similar but benefits grow to $1.2 billion by 2060 and $1.5 billion by 2100. The present value of this stream of benefits to consumers through 2100 is equal to $13 billion in the slow growth scenario and $14 billion in the fast growth scenario.

**Table 7. Impact of global warming on California consumers (millions of dollars)**

| | | Annual impact | | |
|---|---|---|---|---|
| | **Present value** | **2020** | **2060** | **2100** |
| **Slow growth** | | | | |
| State | 13,156 | 490 | 1,000 | 1,000 |
| South | 8,077 | 301 | 614 | 614 |
| Central coast | 2,717 | 101 | 206 | 206 |
| Central valley | 1,719 | 64 | 131 | 131 |
| North coast | 270 | 10 | 21 | 21 |
| North interior | 173 | 6 | 13 | 13 |
| Sacramento | 200 | 7 | 15 | 15 |
| **Fast growth** | | | | |
| State | 14,280 | 486 | 1,157 | 1,537 |
| South | 8,767 | 298 | 710 | 944 |
| Central coast | 2,949 | 100 | 239 | 317 |
| Central valley | 1,866 | 64 | 151 | 201 |
| North coast | 293 | 10 | 24 | 32 |
| North interior | 188 | 6 | 15 | 20 |
| Sacramento | 217 | 7 | 18 | 23 |

Consumers all across the state will gain from the lower prices but counties will gain in proportion to population. Even counties that have no timber production will enjoy gains in consumer surplus. This is especially evident in the southern urban counties that gain about 60% of the benefits and in the San Francisco region that enjoys another 20%. The remainder of the benefits is spread across the more rural parts of the state. Because the timber growing northern and mountain regions have relatively low populations, they receive only a small fraction (5%) of the statewide consumer benefits.

# 2. Conclusions

This appendix presents estimates of the welfare impacts of climate change on California timber. We have explored several climate scenarios that exhibit a range of temperature and precipitation changes. Two of the scenarios involve GCMs scaled down to the 10 km level. We then employed a detailed dynamic ecological model to predict how the state's forests are likely to change. This reliance on an ecological model to predict dynamic ecological outcomes is one of the methodological advances of this study. The ecological model predicts that productivity per acre will increase in most scenarios but that the acreage of softwoods will likely decline. Next, we used an economic model to determine how these ecological changes will affect planting, harvesting, and net revenues over time.

Assuming no change in prices, the economic model predicts that net revenues will increase at first in all scenarios because of the increase in productivity. As time passes, some of the scenarios predict that net revenue will subsequently decline, even below baseline levels, whereas others predict continued increases in net revenues. The present value of all these scenarios is strictly beneficial. The early increases in net revenue outweigh the later declines in scenarios that show decline. When we examine productivity effects directly, it would appear that California timber markets would benefit under climate change even though many scenarios predict deleterious long-term impacts.

We also examined how California timber will do if climate change changes global prices. Using the results of a global timber model, we predict that timber prices will fall over time as world productivity increases. These falling prices will cause net revenues in California to fall dramatically over time in every scenario. The present value of damages to timber producers is more than $1 billion in many cases. These losses result largely from the price effects, however, and not from the reductions in softwood area predicted by the model. The reductions in global prices, however, lead to large gains for consumers. The predicted increase in present value for California consumers are in the neighborhood of $14 billion. The net result is that warming might provide net timber benefits to California by providing lower prices for timber consumers.

This research indicates a wide range of possible effects on California's timber resource. Part of the uncertainty lies in the climate scenarios themselves because the state may experience mild or severe warming and dry or wet conditions. This range of climate outcomes will lead to different predictions of productivity changes and of biome changes. However, most of the scenarios imply that productivity changes will likely be positive and the biome changes will be negative for timber. The research, however, highlights that timber resources in California are even more sensitive to changes in global timber prices. If forests in the rest of the world increase in productivity as much as many models predict, prices for timber will fall, making climate change harmful to California producers but beneficial to consumers. The effects of climate change outside the state may be even more important than the observed effects in the state.

Several limitations of the current study could be addressed in future work. As part of the unifying conditions set forth in this study to make the results consistent across sectors, the study was limited to the period between 2000 and 2100. This leads to the conspicuous omission of effects beyond 2100 that may underestimate damages in the timber sector. In addition, the study explores the importance of global prices but relies on a global model for price predictions that is not perfectly consistent with the California model; that is, the climate scenario explored in the global model is not exactly the same scenario used in the state study. The price effects must be interpreted cautiously.

# References

Bachelet, D., J. Lenihan, C. Daly, R. Neilson, D. Ojima, and W. Parton. 2001. MC1: A Dynamic Vegetation Model for Estimating the Distribution of Vegetation and Associated Ecosystem Fluxes of Carbon, Nutrients, and Water. General Technical Report PNW-GTR-508. U.S.D.A. Forest Service, Pacific Northwest Station.

Binkley, C.S. 1988. A case study of the effects of $CO_2$-induced climatic warming on forest growth and the forest sector: B. Economic effects on the world's forest sector. In *The Impact of Climatic Variations on Agriculture,* M.L. Parry, T.R. Carter, and N.T. Konijn (eds.). Kluwer, Dordrecht.

Bowes, M. and R. Sedjo. 1993. Impacts and responses to climate change in forests of the MINK region. *Climatic Change* 24:63-82.

Burton, D.M., B.A. McCarl, N.M. de Sousa, D.M. Adams, R.A. Alig, and S.M. Winnet. 1998. Economic dimensions of climate change impacts on southern forests. In *Ecological Studies 128: The Productivity and Sustainability of Southern Forest Ecosystems in a Changing Environment,* S. Fox and R. Mickler (eds.). Springer-Verlag, New York.

Dai, A., T.M.L. Wigley, B.A. Boville, J.T. Kiehl, and L.E. Buha. 2001. Climates of the twentieth and twenty-first centuries simulated by the NCAR Climate System Model. *Journal of Climate* 14:485-519.

Daly, C., D. Bachelet, J. Lenihan, W. Parton, R. Neilson, and D. Ojima. 2000. Dynamic simulations of tree-grass interactions for global change studies. *Ecological Applications* 10:449-469.

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson. 1985. Climate change and the broad-scale distribution of terrestrial ecosystem complexes. *Climatic Change* 7:29-43.

Gitay, H., S. Brown, W. Easternling, and B. Jallow. 2001. Ecosystems and their goods and services. Chapter 5 in *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds.). Cambridge University Press, Cambridge, UK, pp. 235-342.

Johns, T.C., R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Mitchell, C.A. Senior, S.F.B. Tett, and R.A. Wood. 1997. The second Hadley Centre coupled ocean-atmosphere GCM: Model description, spinup and validation. *Climate Dynamics* 13:103-134.

Joyce, L.A., J.R. Mills, L.S. Heath, A.D. McGuire, R.W. Haynes, and R.A. Birdsey. 1995. Forest sector impacts from changes in forest productivity under climate change. *Journal of Biogeography* 22:703-713.

Lenihan, J.M., C. Daly, D. Bachelet, and R.P. Neilson. 1998. Simulating broad-scale fire severity in a dynamic global vegetation model. *Northwest Science* 72:91-103.

McCarl, B.A., D.M. Adams, R.D. Alig, D. Burton, and C. Chen. 2000. The effects of global climate change on the U.S. forest sector: Response functions derived from a dynamic resource and market simulator. *Climate Research* 15(3):195-205.

Melillo, J.M., A.D. McGuire, D.W. Kicklighter, B. Moore III, C.J. Vorosmarty, and A.L. Schloss. 1993. Global climate change and terrestrial net primary production. *Nature* 363:234-240.

Neilson, R.P. and D. Marks. 1994. A global perspective of regional vegetation and hydrologic sensitivities from climate change. *Journal of Vegetation Science* 5:715-730.

Shugart, H.H., M.Y. Antonovsky, P.G. Jarvis, and A.P. Sandford. 1986. $CO_2$, climatic change, and forest ecosystems. Chapter 10 in *The Greenhouse Effect, Climatic Change and Ecosystems,* B. Bolin, B.R. Doos, J. Jager, and R.A. Warrick (eds.). Wiley, Chichester, UK.

Sohngen, B. and R. Mendelsohn. 1998. Valuing the market impact of large scale ecological change in a market: The effect of climate change on U.S. timber. *American Economic Review* 88:686-710.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 1999. Forest conservation, management, and global timber markets. *American Journal of Agricultural Economics* 81(1):1-13.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 2002. A global model of climate change impacts on timber markets. *Journal of Agricultural and Resource Economics* 26:326-343.

Solomon, A.M. 1986. Transient response of forest to $CO_2$-induced climate change: Simulation modeling experiments in eastern North America. *Oecologia* 68:567-579.